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International Workshop on Quantum Cascade Lasers

MEETING PROGRAM, ABSTRACT BOOK & ATTENDEE ROSTER

January 4 – 8, 2004
Seville, Spain

Sponsored by:

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A thank you to our Workshop supporters...

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AFOSR manages all basic research conducted by the U.S. Air Force. One of the tools used to accomplish this task is to solicit proposals for research. AFOSR also conducts collegial scientific workshops for the purpose of forming partnerships with in-house and extramural (contractor and grantee) researchers in common areas of research. The Air Force also sponsors research assistantship programs, faculty programs, and graduate school programs.

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Maxion Technologies, Inc.

Maxion Technologies, Inc. develops quantum cascade (QC) and interband cascade (IC) semiconductor diode lasers specifically designed to enable a wide range of applications, including portable chemical sensing, broadband wireless communications, and infrared countermeasures. Maxion's mission is to become the leading provider of mid-infrared diode lasers to the business, government, and research communities.

Program Schedule
International Workshop on Quantum Cascade Lasers

Sunday, January 4th, 2004

Please join us for the Welcoming Reception on Sunday evening, from 7:00 to 9:00 p.m. at the Hotel Becquer. Spouses and guests are welcome!

Monday, January 5th, 2004

Breakfast: 7:45 - 8:45 a.m.	
8:45 a.m. – Welcoming Remarks: Todd Steiner	
8:50 a.m. – Introduction: Federico Capasso	
Session 1: Applications	**Chair: Serge Luryi**
9:00 a.m. – 9:30 a.m. (Scene-setter)	**Frank Tittel:** Current applications of quantum cascade lasers in trace gas analysis and chemical sensing (Page 5)
9:30 a.m. – 9:50 a.m.	**Mattias Beck:** State-of-the-Art Mid-infrared Quantum Cascade Lasers (Page 7)
9:50 a.m. – 10:10 a.m.	**Frank Fuchs:** InP-based Single-Mode Quantum Cascade Lasers for Trace-Gas Sensing Applications (Page 9)
Session 2: Mid-IR Type I and Type II Cascade Lasers	**Chair: Todd Steiner**
10:10 a.m. – 10:40 a.m. (Scene-setter)	**Jerry Meyer:** Projected Performance Trade-Offs for Interband *vs.* Intersubband Quantum Cascade Lasers; also stands in for Rui Yang: Progress and Challenges in the Development of Interband Cascade Lasers (Pages 11 & 13)
Break: 10:40 a.m. – 11:10 a.m.	
11:10 a.m. – 11:30 a.m.	**Gregory Belenky:** Recent Performance Advances in Type II Interband Cascade Lasers (Page 15)
11:30 a.m. – 11:50 a.m.	**Manijeh Razeghi:** The Route to High-Power, Continuous-Wave, Quantum Cascade Lasers at Room Temperature (Page 17)
11:50 a.m. – 12:10 p.m.	**Jim Speck:** Progress in GaN growth in non-polar orientations and in GaN MBE growth (Page 19)
12:10 p.m. – 12:30 p.m.	**John Cockburn:** High performance quantum cascade lasers grown by metal-organic vapour phase epitaxy (Page 21)
12:30 p.m. – 12:50 p.m.	**Gaetano Scamarcio:** Micro-probe luminescence and Raman investigation of quantum cascade lasers: correlation with optical performance (Page 23)
Lunch: 1:00 p.m. – 2:30 p.m.	
Interactive Session: 2:30 – 4:00 p.m.	
Stroll Seville and enjoy the parade of the Fiesta de Los Reyes (Three Kings) celebrating when the three kings of Orient bring their Christmas presents to the children. Three men dress up as the kings, and ride about the town in a procession, scattering sweets to the crowds of excited children.	
7:45 p.m. – Gather in lobby to walk to dinner. 8:00 p.m. – 10:00 p.m. – **Dinner at Salvador Rojo Restaurant**. We'll enjoy a stroll to the nearby restaurant to enjoy a delicious Spanish dinner.	

Tuesday, January 6th, 2004

Breakfast: 8:00 - 9:00 a.m.

Session 3: Novel Structures I — Chair: Federico Capasso

9:00 a.m. – 9:30 a.m. (Scene-setter)	**Claire Gmachl:** Nonlinear light generation in Quantum Cascade lasers (Page 25)
9:30 a.m. – 9:50 a.m.	**H. C. Liu:** Intersubband Raman Lasing and Coupled Electronic-Phonon Modes (Page 27)
9:50 a.m. - 10:10 a.m.	**Mariano Troccoli:** Far-Field Control and Beam Steering in Quantum Cascade Lasers (Page 29)
10:10 a.m. – 10:30 a.m.	**Serge Luryi:** Distributed Feedback Quantum Cascade Laser with Widely Tunable Wavelength (Page 31)
10:30 a.m. - 10:50 a.m.	**Raffaele Colombelli**: Quantum Cascade Photonic-Crystal Microlasers (Page 33)

Break 10:50 a.m. – 11:30 a.m.

Session 4: Novel Structures II — Chair: Mark Taylor

11:30 a.m. – 12:00 noon (Scene-setter)	**Carlo Sirtori:** Material systems for quantum cascade lasers (Page 35)
12:00 noon – 12:20 p.m.	**Mikhail Kisin:** Enhancement of the Phonon Depopulation in Intersubband Cascade Lasers (Page 37)
12:20 p.m. – 12:40 p.m.	**Hans Sigg:** Towards Si-based Quantum Cascade Lasers: Challenges and Achievements (Page 39)
12:40 p.m. – 1:00 p.m.	**Dan Botez:** Intersubband Quantum-Box Semiconductor Lasers (Page 41)
1:00 p.m. – 1:20 p.m.	**Dennis Deppe:** Self-organized epitaxial nanostructures for quantum dot cascade lasers (Page 43)

1:30 – 3:00 p.m. **Lunch**

Interactive Session: 3:00 p.m. – 4:30 p.m.

6:30 p.m. – 8:00 p.m. – Dinner at Hotel Becquer

8:15 – Depart lobby to walk to Los Gallos for a Flamenco Show – the best in town! – from 9:00 – 11:00 p.m.

Wednesday, January 7th, 2004

Breakfast: 7:45 – 8:45 a.m.

Session 5: THz Cascade Lasers — Chair: Carl Kutsche

8:45 a.m. – 9:15 a.m. (Scene-setter)	**Jérôme Faist:** Ultimate limits in THz and mid-IR QC lasers (Page 45)
9:15 a.m. – 9:35 a.m.	**Rüdeger Köhler:** Terahertz Quantum Cascade Lasers (Page 47)
9:35 a.m. – 9:55 a.m.	**Qing Hu:** THz Quantum Cascade Lasers Based on Phonon-Assisted Depopulation (Page 49)
9:55 a.m. – 10:15 a.m.	**Richard Soref:** Terahertz Quantum-Staircase and Quantum-Parallel Laser Designs for GaAs/AlGaAs and SiGe/Si (Page 51)
10:15 a.m. – 10:35 a.m.	**Bill Goodhue:** THz Quantum Cascade Laser Design and Application (Page 53)
10:35 a.m. – 10:55 a.m.	**Karl Unterrainer:** Field Control of THz Quantum Cascade Lasers (Page 55)

Break: 10:55 a.m. – 11:15 a.m.

Session 6: Novel Phenomena and Physics — Chair: Jérôme Faist

11:15 a.m. – 11:45 a.m. (Scene Setter)	**Paul Harrison:** A Physical Model of Quantum Cascade Lasers: Application to GaAs, GaN and SiGe devices (Page 57)
11:45 a.m. – 12:05 p.m.	**Michael Woerner:** Ultrafast coherent electron transport in quantum cascade structures (Page 59)
12:05 p.m. – 12:25 p.m.	**Emilio Mendez:** Electronic Transport in Quantum-Cascade Heterostructures (Page 61)
12:25 p.m. – 12:45 p.m.	**Franz Kaertner:** Mode Locking of Quantum Cascade Lasers (Page 63)
12:45 p.m. – 1:05 p.m.	**Federico Capasso:** Modelocking of broadband QC lasers (Page 65)

1:05 p.m. – 2:35 p.m. - Lunch

2:30 p.m. - Depart hotel promptly at 2:30 for Tour of Seville. We will start by bus to discover the Seville of the past, present and future. We will make a marvelous boat trip along the Guadalquivir River and enjoy some of the most attractive panoramic views of Seville. We will continue with sightseeing of the most famous pavilions and bridges of the 1992 universal exposition and we will visit the Cartushian Monastery, where Columbus thought about the sea and life. Finally we will go to the Basilica of the Macarena where we can see part of the holy week in Seville. Return to the hotel at approximately 5:45. Return to hotel at approximately 5:45 p.m. **SPONSORED BY MAXION TECHNOLOGIES, INC.**

6:00 p.m. – 7:30 p.m. Wrap-up Session. The Wrap-up session provides an opportunity for participants to gather to summarize the findings/technical information shared throughout the week. It's also the last opportunity to obtain answers to questions that time may not have allowed during the session. All participants are requested to participate. Wine and beer will be served.

8:00 – 9:30 p.m. **Dinner at the Hotel Becquer**

Thursday, January 8th, 2004

8:30 a.m. – 10:00 a.m.	**Breakfast/Collaboration:** Join together for a final breakfast designed to ensure that you have made plans for future collaborations with colleagues.

Current applications of quantum cascade lasers in trace gas analysis and chemical sensing

Frank K. Tittel, Yury. Bakhirkin, Robert F. Curl, Anatoliy, A.Kosterev, Matt McCurdy C.Roller, Stephen So, D.Weidmann, and G.Wysocki.
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Phone (713 348 4833, Fax: 713 348 5686, fkt@rice.edu, www.ece.rice.edu/lasersci

One of the principal applications of quantum cascade lasers (QCLs) is in chemical sensing, since these lasers can access directly the mid-infrared spectroscopic fingerprint region (~2-25 μm), where most gaseous chemical substances possess strong fundamental rotational-vibrational transitions [1-3]. To date we have detected 11 gases (CH_4, N_2O, CO_2, CO, NO, H_2O, NH_3, C_2H_4, COS , SO_2 and C_2H_5OH including isotopic signatures of carbon and oxygen at the ppm to the ppb level using QCLs. This talk will focus on the development of compact trace gas sensor platform technology based on QCLs and their application to sensitive, selective and quantitative trace gas detection. Current application topics include: atmospheric chemistry and environmental monitoring, urban and industrial emissions measurements, chemical analysis and industrial process control and medical applications

QCLs possess the key properties required for a mid-infrared spectroscopic source: (1) sufficient optical power to ensure high signal-to-noise ratios, (2) narrow linewidths and single frequency to obtain high selectivity (3) mid-infrared wavelength coverage with type I and II QCLs (4) continuous and broad wavelength tunability without mode hops, (5) quasi-room temperature operation (6) good beam quality and (7) high reliability and compactness. Until recently quasi-room temperature operation of QCLs was only possible for pulsed operation, but recently the first thermoelectrically-cooled, continuous wave (cw), mid-infrared, single frequency QCL was reported, which will greatly facilitate the use of QCLs in spectroscopic applications [4]

Current examples of QCL applications being investigated by us include trace gas sensing in NASA applications relevant to spacecraft environmental monitoring and advanced life support using quartz enhanced photoacoustic spectroscopy, high precision measurements of $^{13}CO_2/^{12}CO_2$ isotopic ratios at 4.3 μm and noninvasive medical diagnostics of various human diseases by means of breath analysis. One specific application is the measurement of NO in exhaled breath, since the presence of NO is an indicator of several physiological and biochemical processes taking place in the human body, in particular in assessing the severity of airway inflammation (i.e. asthma). A gas sensor based on a cw single frequency QCL operating at ~5.2 um (1900 cm-1) and off axis integrated cavity output spectroscopy is being developed to measure ppb levels of NO concentration in breath.

References:

1. F.Gmachl, C.Gmachl, R.Paiella, A.Terdicucci, D.L.Sivco, J.N.Baillargeon and A.Y.Cho. "New Frontiers in quantum cascade lasers and applications", IEEE Select. Topics Quantum Electron. **6**, 931-947 (2000)
2. A.A. Kosterev and F.K.Tittel, "Chemical Sensors based on Quantum Cascade Lasers", IEEE J.Quant. Electron. **38,** 582-591 (2002)
3. F.K.Tittel, D.Richter and A.Fried, "Mid-Infrared Laser Applications in Spectroscopy" in *Solid –State Mid-Infrared Laser Sources,* eds. I.T Sorikina and K.L. Vodopyanov Topics Appl. Phys. **89**, 445-510 (2003) Springer-Verlag
4. T.Aellen, S. Blaser, M.Beck, D. Hofstetter, J.Faist and E.Gini, " Continuous-wave distributed-feedback quantum-cascade lasers on a Peltier cooler", Appl. Phys.Lett **83**, 1929-1931 (2003).

NOTES

State-of-the-Art Mid-infrared Quantum Cascade Lasers

Mattias Beck, University of Neuchatel, Switzerland

Mid-infrared QCLs feature high threshold current densities J_{th} - typically exceeding some kA/cm^2 at room temperature - and a high bias voltage. Nevertheless, continuous wave operation could be achieved at room temperature or even higher with extremely large optical power levels with structures based on 4-quantum-well active regions with low J_{th} and using an optimized device geometry with improved heat dissipation.

In this presentation we will discuss the dependence of J_{th} on the doping level of a 4-quantum-well design and compare 3 different active region designs (3-quantum-well, 4-quantum-well, and chirped superlattice design) in terms of J_{th}, bias voltage and optical power. J_{th} – values as low as 1.1kA/cm^2 could be achieved at room temperature. The MBE influence on performances will also be discussed.
Time-resolved measurements of a grating-coupled external cavity configuration with a tuning range of over 150 cm^{-1} will also be presented.

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InP-based Single-Mode Quantum Cascade Lasers for Trace-Gas Sensing Applications

F. Fuchs, Ch. Mann, Q. K. Yang, W. Bronner, and K. Köhler
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email: frank.fuchs@iaf.fraunhofer.de

Quantum cascade (QC) lasers have attracted much interest in the past few years. For applications in trace-gas sensing single-mode emission is required. Two operating schemes will be discussed: continuous-wave (cw) operation of Fabry-Perot (FP) QC lasers at low temperature and pulsed operation of distributed feedback (DFB) QC lasers at room temperature.

In cw operation single-mode emission is observed near threshold for FP QC lasers and a maximum operating temperature of 222 K is determined for epi-side down mounted devices with high-reflection (HR) coated facets. Fig. 1 shows the measured cw output power vs. current (L-I) characteristics at various heat-sink temperatures between 84 K and 222 K together with the voltage vs. current (V-I) dependence at 84 K of a 7 x 1000 μm^2 QC laser emitting at 5.1 μm. Although the dissipated electrical power is reduced compared to devices with as-cleaved facets, cw operation at higher temperature is still limited by heating of the active region due to the low thermal conductivity in growth direction.

To avoid the need for cryogenic cooling DFB QC lasers were fabricated. These devices show single-mode emission in pulsed operation (100 ns pulse width, 5 kHz repetition rate) for heat-sink temperatures between 240 K and 350 K (see Fig. 2).

Under the present operating conditions FP QC lasers operated in cw mode at cryogenic temperatures were successfully applied in CO detection experiments. DFB QC lasers operated in pulsed mode at room-temperature were employed for the detection of NO.

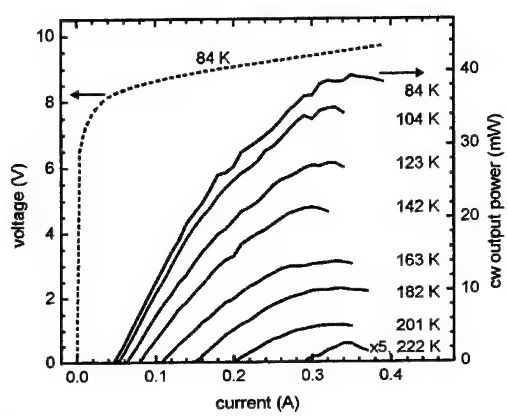

Fig. 1. Temperature-dependent cw (L-I) characteristics (solid, right axis) and (V-I) dependence at 84 K (dashed, left axis) of a 5.1 μm FP QC laser mounted epi-side down with HR-coated facets

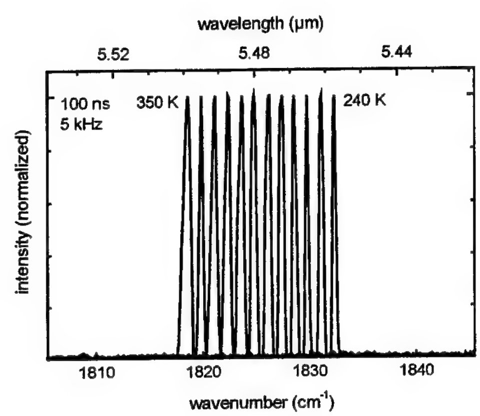

Fig. 2. Temperature dependent pulsed (100 ns pulse width, 5 kHz repetition rate) single-mode lasing spectra of a DFB QC laser covering the 240 K to 350 K temperature interval (step width: 10 K)

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Projected Performance Trade-Offs for Interband *vs.* Intersubband Quantum Cascade Lasers

J. R. Meyer and I. Vurgaftman
Code 5613, Naval Research Laboratory, Washington DC 20375

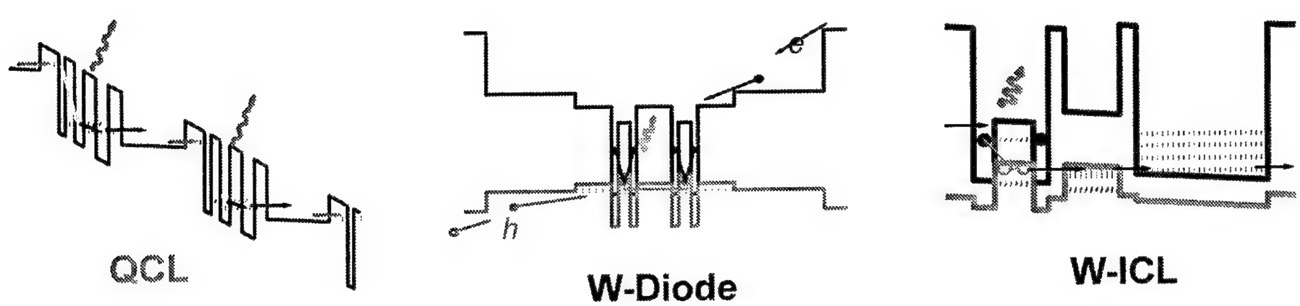
This talk will address the question of which mid-IR semiconductor laser approach has the best prospects for generating high cw output powers at ambient temperature or with thermoelectric cooling. Emphasis will be on the 3-5 μm spectral range, and on projected long-term potential rather than achievements to date.

The unipolar quantum cascade laser (QCL) derives gain by inverting the population of two conduction subbands. Its advantages include multiple stages for high slope efficiency, small threshold carrier density, high characteristic temperature, relatively-mature material systems (InP- or GaAs-based), and low linewidth enhancement factor for enhanced beam quality. Accompanying disadvantages are higher threshold due to a short phonon relaxation lifetime, greater heat dissipation to reach threshold due to the multiple stages, and the need for strain compensation to reach wavelengths shorter than 5 μm.

The antimonide type-II "W" laser is an interband device with higher differential gain, better electrical confinement, and less Auger decay than earlier type-I interband mid-IR diodes. Compared to the QCL, its potential advantages include lower threshold due to longer lifetime and lower heat dissipation at threshold due to its single stage. Disadvantages include the immaturity of GaSb-based growth and processing, lower slope efficiency, and lower T_0.

The interband cascade laser also a type-II antimonide interband device, which usually employs a similar "W"-shaped active region. However, like the QCL it has multiple stages that are joined via interband scattering at a type-II interface. It therefore combines the higher slope efficiency of the QCL with the longer lifetime of the conventional diode. A further variation that may prove advantageous is an ICL with only enough stages (*e.g.*, ≈ 5) to provide net gain.

This presentation will analyze the relative strengths and weaknesses of each approach, and strategies for optimizing the output. Thermal management considerations, which differ for each type of laser, are crucial to the ultimate performances. Minimizing the heat dissipation required to reach threshold is one important consideration, which can potentially benefit from a reduction of the number of active periods. Another key issue is whether it is advantageous to employ several narrow (single-lateral-mode) stripes that are then incoherently combined, or one broad stripe with a photonic crystal distributed feedback grating to enhance the beam quality. A further perspective is that there will probably continue to be some boundary wavelength, below which ICLs are advantageous and beyond which QCLs are preferable.



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Progress and Challenges in the Development of Interband Cascade Lasers

Rui Q. Yang and Cory J. Hill (Presented by Jerry Meyer)
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Mid-infrared interband cascade (IC) lasers re-use injected electrons by taking advantage of the broken band-gap alignment in Sb-based type-II quantum wells (QWs) to form cascade stages [1], leading to a quantum efficiency greater than the conventional limit of unity. IC lasers were projected by early theories [2, 3] of being capable of operating in continuous wave (cw) mode up to room temperature with high output power due to some advantages of type-II QWs and their utilization of interband transitions for photon emission without involving fast phonon scattering. Significant progress toward such a high performance level has recently been made at JPL [4-7] in terms of low threshold current densities (e.g. ~9 A/cm^2 at 80 K) and high temperature operation (e.g. 325 K in pulsed and 200 K in cw modes). These accomplishments were achieved even though in-house device fabrication and packaging were in a preliminary stage and still being perfected, and the mesas were relatively wide with large specific thermal resistance. The observed threshold current densities from our IC lasers are already below any previously reported value among mid-IR lasers at a wide temperature range from 80 K up to room temperature. These accomplishments suggest the high likelihood of IC lasers achieving cw operation near room temperature with relatively high output power when advanced device fabrication/packaging techniques such as facet coating, epi-side-down mounting, and narrow-ridge formation are applied in combination with further improvements in device design and MBE-grown material quality.

We will briefly review our progress and present some recent results such as cw operation of single-mode distributed feedback IC lasers. Challenges and unsolved issues in the development of mid-IR IC lasers will be also discussed.

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2. J. R. Meyer, I. Vurgaftman, R. Q. Yang, and L. R. Ram-Mohan, Electronics Letters, **32**, 45 (1996).
3. I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, IEEE Photo. Tech. Lett. **9**, 170 (1997).
4. R. Q. Yang, C. J. Hill, B. Yang, J. K. Liu, Appl. Phys. Lett. **15**, 2109 (2003).
5. C. J. Hill, B. Yang, R. Q. Yang, Proceedings of 11th Intl. Conf. on Narrow-Gap Semiconductors, June 16-20, Buffalo, NY, USA (to be published in Physica E).
6. R. Q. Yang, C. J. Hill, B. Yang, J. K. Liu, Digest of 30th International Symposium on Compound Semiconductors, pp. 211-212, Aug. 25-27, 2003, San Diego, CA, USA.
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NOTES

Recent Performance Advances in Type II Interband Cascade Lasers

J.D. Bruno, G. Belenky [a], S. Suchalkin [a], R. Tober[b]
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Type II Interband Cascade Lasers (ICLs) combine the efficiency advantages of cascade injection with those of interband optical transitions resulting in a design capable of high temperature, CW operation. Experimental study showed that a decreasing optical gain with increasing temperature is responsible for limiting the ICLs high temperature, CW performance. At temperatures higher than 140 K, the optical gain shows strong saturation with increasing current, which is found to be due to active region overheating. The temperature dependence of the optical loss is relatively weak: the internal loss increases from ~ 40 cm^{-1} at 80K to ~ 60 cm^{-1} at 200K. We demonstrate that the appearance of strong modulation in the modal gain spectrum is due to optical mode leakage into the substrate. Improved device packaging using a thick electroplated Au contact significantly reduces the ICLs thermal resistance (by as much as ~ 40% for 1-mm-long devices). Newly packaged ICLs show a CW power conversion efficiency of 23% and a differential external quantum efficiency of 532% at 80K. A maximum CW operating temperature of 214K was demonstrated. The comprehensive characterization of the lasers with different mesa widths shows that the higher threshold current density in devices with narrow mesas is caused by the relatively increased importance of the mesa-edge surface recombination contribution to the average carrier lifetime in narrower mesa devices. Recent work in these areas will be reviewed and updated.

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The Route to High-Power, Continuous-Wave, Quantum Cascade Lasers at Room Temperature

M. Razeghi, S. Slivken, J.S. Yu, K. Mi, S. Darvish,
V. Yazdanpanah, A. Evans, L. Doris, J. David
*Center for Quantum Devices, Dept. of Elect. and Comp. Engineering,
Northwestern University, Evanston, IL 60208*

This talk will go over the systematic methodology that is necessary for optimization of quantum cascade performance at room temperature. Emphasis will be placed first on the use of a robust design, which is subdivided into band structure, waveguide, and thermal elements. Band structure is simulated numerically for arbitrary electric fields. Efficient electron transport is crucial, and care is taken to keep thermal backfilling and continuum leakage low, without adding significant excess voltage to the laser structure. The donor concentration is of particular importance for transport and laser threshold condition at room temperature, and must be optimized for each new structure. For waveguide design, losses due to free-carrier absorption and surface plasmon absorption are kept low, but balanced with the epitaxial thickness and electrical conductivity concerns of the overall device. Similar concerns are present with regard to the waveguide thermal properties, which leads to the use of a thick InP cladding for efficient heat extraction from the active layers.

After the design phase is complete, material quality is of prime concern. Epitaxial growth techniques and conditions will be discussed, along with the material characterization techniques that allow rapid feedback for monitoring of structural parameters and electrical properties. X-ray diffraction is the predominant structural analysis tool, which with simulation allows very sensitive analysis of growth rates and layer composition. Capacitance-voltage profiling, which is possible in GaAs and InP material systems is presented as powerful electrical characterization technique, allowing for run-to-run monitoring of background and intentional doping levels in the active layers. This is an especially important tool when optimizing the injector doping for a given laser design. These techniques have led to the demonstration of room temperature, pulsed lasers emitting 7 W and 1 W of peak power at 9 μm and 11 μm wavelengths respectively.

Laser fabrication and packaging also play a strong role in laser performance. Double-channel and buried ridge waveguide geometries are chosen as the most mechanically robust. Ridge width is investigated, with higher efficiencies being demonstrated for narrower ridges. Efficient heat sinking with electroplated gold, and broadband highly-reflective coatings of high efficiency are demonstrated as routes for high average power operation at room temperature. As a result, 850 mW and 520 mW of average power have been demonstrated from 5.9 μm and 4.5 μm lasers operation at room temperature. Continuous wave operation has also been demonstrated. To date the best results have come from a λ=6 μm buried ridge device with a 9 μm ridge width, which demonstrated 375 mW of continuous power at 298 K.

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Progress in GaN growth in non-polar orientations and in GaN MBE growth

James S. Speck
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In this talk, we review work at UCSB on progress in the growth of GaN in non-polar orientations and the MBE growth of AlN and high-Al content AlGaN. The non-polar nitrides are attractive because of the absence of polarization-induced internal electric fields that are common for c-axis material. We have worked extensively on the HVPE, MOCVD, and MBE growth of a-plane $(11\bar{2}0)$ GaN growth on r-plane $(1\bar{1}02)$ sapphire and a-plane SiC and also on m-plane $(1\bar{1}00)$ GaN growth on m-plane SiC and on (100) LiAlO2. In all cases, direct growth on these substrates results in threading dislocation densities greater than 10^{10} cm^{-2} and basal plane stacking fault densities greater than 10^4 cm^{-1}. We have developed lateral epitaxial overgrowth of a-plane GaN by both HVPE and MOCVD and can now produce large area low defect density non-polar GaN. We will discuss the potential of the non-polar oriented nitrides for QC applications. We demonstrate the absence of the QCSE for a-plane AlGaN/GaN MQW structures and also demonstrate the first p-n diodes for non-polar nitrides. Additionally, highlights of work on direct MBE growth of AlN on (0001) oriented 6H SiC will be presented and contrasted with MOCVD growth of AlN.

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High performance quantum cascade lasers grown by metal-organic vapour phase epitaxy

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Quantum Cascade Lasers (QCLs) have become important, high-quality sources of laser light in the mid-infrared region of the spectrum. Fabrication of these devices is demanding in terms of crystal growth, requiring precise control of large numbers of thin (nm-sized) layers of semiconducting material forming the active regions. Until recently, growth of QCLs has been confined to the high-vacuum technique of molecular beam epitaxy (MBE). Recently, we have demonstrated the growth of QCLs by metal-organic vapour phase epitaxy (MOVPE)[1], a technique which has several potential advantages over MBE. These include reactors that can be readily maintained without the need for elaborate baking cycles to recover from atmospheric contamination, and the ability to controllably alter growth rates over a wide range within a growth run.

We report MOVPE-grown QCLs with a double phonon resonance design. High-resolution X-ray diffraction (XRD) measurements indicate a high degree of reproducibility between growth runs, with ~20 satellite peaks clearly visible over a ~4° range. Fig. 1 shows a typical XRD rocking curve, together with a dynamical simulation of the XRD data. We obtain a close similarity between the measured and simulated curves. The seven wafers grown show a variation of just 3% in the superlattice periods obtained from the XRD, with a ~5meV spread of laser emission energies. Laser emission has been observed from all wafers at ~9μm; low resolution (2 cm^{-1}) laser spectra are shown in Fig. 2, measured at 12K using FTIR spectrometry. Threshold current densities were as low as 840 A cm^{-2} at 12K, and 3.5 kA cm^{-2} at room temperature, comparable to those observed in state of the art MBE grown devices.

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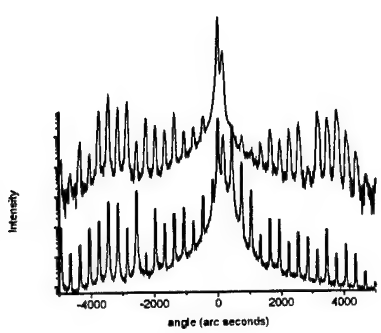

Fig. 1

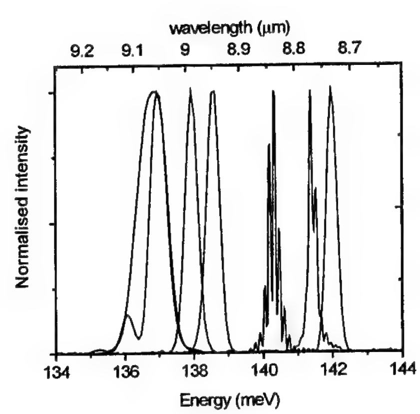

Fig. 2

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Micro-probe luminescence and Raman investigation of quantum cascade lasers: correlation with optical performance

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The experimental knowledge of energy relaxation phenomena, the understanding of their interplay with the electrical and optical characteristics, and the design of viable improved schemes to limit the dissipated electrical power and the inherently high thermal resistance are key issues for the further development of quantum cascade lasers. To address these topics, we have exploited an experimental approach based on the simultaneous measurement of band-to-band photoluminescence and Stokes/anti-Stokes Raman spectra in operating QCLs. We have demonstrated the efficacy of this method to determine: (i) the facet temperature profile; (ii) the thermal resistance; (iii) the thermoelastic strain; (iv) the non-equilibrium phonon population; (v) the electronic temperature of excited subbands. We have compared the above results in different device structures as a function of the lattice temperature, the injected current either in CW or pulsed mode. After a brief overview of the rationale and critical features of our approach, my talk will mainly focus on the following subjects:

(a) The simultaneous determination of electronic and lattice temperatures in GaAs/AlGaAs mid-IR quantum cascade lasers shows the establishment of a thermalized hot electron distribution. These results validate a method based on the analysis of light-current and current-voltage characteristics to determine the device thermal resistance and active region mean temperature. Comparing $Al_xGa_{1-x}As$ mole fractions $x = 0.3$ and $x = 0.45$ we have shown that the coupling between the electronic ensemble and the lattice increases with the band-offset. We believe that our approach will be particularly useful to address the issue of carrier energy distribution and energy relaxation processes in THz QCLs. Related aspects will be discussed during the workshop.

(b) A steady-state non-equilibrium optical phonon population may be generated by electron transport in a quantum cascade structure. Possibilities to enhance a quasi-monochromatic phonon generation and eventually stimulated phonon emission in a three terminal device will be discussed. A similar approach has been recently used by us to generate continuously tunable infrared emission in the 100 - 240 meV energy range.

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Nonlinear light generation in Quantum Cascade lasers

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Quantum Cascade (QC) lasers [1] are semiconductor injection lasers based on electronic intersubband transitions. Electrons traverse the cascade of many active regions and injectors one after the other; as a result it is possible to selectively replace active regions and/or injectors with other optical elements such as active regions of another wavelength, which leads to multiple wavelength emission, or nonlinear optical elements, the topic of this presentation. Nonlinear optical transitions can also directly be integrated with the active regions and injectors.

It was known from pioneering work since the late 1980s that intersubband transitions in asymmetric coupled quantum wells can display giant nonlinear optical susceptibilities [2, 3]. However, coupling of an external pump laser to the quantum wells in the required in-plane geometry is cumbersome and phase matching was not achieved. Recently, intra-cavity wave mixing has been proposed for interband semiconductor lasers [4] as an efficient mechanism to combine pump and mixing nonlinearity, and has been demonstrated for QC lasers in reference 5.

The monolithic integration of resonant optical nonlinearities based on intersubband transitions and QC lasers has several beneficial aspects. First, both are based on intersubband transitions and can therefore be integrated with each other in very close proximity, even within the same set of quantum wells; second, QC lasers can be very powerful efficient pump sources with power densities approaching MW/cm^2; third, QC laser waveguides provide sufficient flexibility for true phase matching of the fundamental and nonlinear modes of different mode order.

Here, we will discuss several recent developments in QC lasers with integrated optical nonlinearities, namely efficient second harmonic generation (SHG) in conventional [6] and phase-matched [7] waveguides. We will furthermore discuss the prospects of higher harmonics generation, of several schemes of frequency down-conversion, and resonant Anti-Stokes Raman scattering.

We are focusing here at resonant optical nonlinearities, nonlinear light generation using the bulk optical nonlinearity of QC laser material grown on (111) oriented has also recently been reported [8].

QC lasers have been designed with active regions that simultaneously contain nonlinear optical cascades of resonantly coupled intersubband transitions with giant second-order nonlinearities. QC-lasers with 3-coupled quantum well active regions showed up to 2 μW of SHG light at 3.75 μm wavelength at a fundamental peak power and wavelength of 1 W and 7.5 μm, respectively [6]. These lasers resulted in an external linear to nonlinear conversion efficiency of up to 1 μW/W^2. An improved 2-QW active region design at fundamental and SHG wavelengths of 9.1 and 4.55 μm, respectively, resulted in a 100-fold improved external linear to nonlinear power conversion efficiency; i.e. up to 100 μW/W^2 [6]. Full theoretical treatment of nonlinear light generation in this active region results in a second-order nonlinear susceptibility of 2×10^4 pm/V. An additional about 100-fold improvement of the SHG efficiency was then obtained by including phase-matching considerations in the design of the deep-etched ridge waveguide. The waveguide layer structure was designed to minimize the phase-mismatch of the zero order mode of the fundamental light with the second-order transverse mode of the second-harmonic light [7, 9]. Exact phase-matching is then achieved by appropriately tailoring the ridge. Up to 240 μW of SHG power and a nonlinear power conversion efficiency of up to 36 mW/W^2 were achieved [7].

The work performed at Bell Laboratories was partly supported by DARPA/US ARO under contract number DAAD19-00-C-0096. A.B acknowledges support from TAMU TITF Initiative and the ONR. We would like to acknowledge fruitful discussions with F. Capasso of Harvard University and Alfred Y. Cho at Bell Laboratories.

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NOTES

Intersubband Raman Lasing and Coupled Electronic-Phonon Modes

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An intersubband Raman laser has been achieved based on a stimulated resonant Raman process in GaAs/AlGaAs 3-level double-quantum-well structures. A CO_2 laser in resonance with the 1-to-3 transition is used as the pump, while the lasing emission occurs via the 3-to-2 transition. The 1-to-2 level spacing is designed to be in near resonance with one of the longitudinal optical phonon modes of the structure, favoring the Raman process. Intersubband lasing at 12 – 16 μm is reported. The presence, or lack of, lasing action provides evidence for resonantly coupled modes of collective electronic intersubband transitions and longitudinal optical phonons. An anticrossing behavior of these modes is clearly seen when the difference between the pump and lasing energies (i.e., Stokes Raman shift) is compared with the subband separation. This work shows the alternative optical pumping scheme (vs. electrical in the usual QCLs) and the physics revealed with this approach. This work presents an alternative mechanism for realizing intersubband lasers and opens up new possibilities in reaching the far infrared region and achieving room temperature operation. This work also demonstrates the significance of the strong coupling between intersubband transitions and phonons, and raises a new possibility of realizing a "phonon" or a "polaron" laser.

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Far-Field Control and Beam Steering in Quantum Cascade Lasers

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In this talk we present some devices recently realized that allow to modify and control the spectral, far-field, and power emission characteristics of quantum cascade lasers. Starting from the realization of a quantum cascade optical amplifier, which allows to obtain single-mode operation with high output powers and beam quality dramatically improved respect to the conventional ridge mesa quantum cascade lasers, we will move on to a modified amplifier device, with a completely tapered waveguide geometry and a specifically patterned contact layout that allows to control the radiation intensity profile as a consequence of the asymmetric charge distribution created by the peculiar injection characteristics. This kind of device allows to modify the position of the main peak in the far field by varying the amount of current injected into a suitably shaped metal contact. The peak shift amounts to its full width at half maximum (~5deg) and can be operated either in continuous or in "switch" mode. In the last part, a brief overlook at how the far-field characteristics can be controlled in vertically emitting photonic crystal devices will be given.

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Distributed Feedback Quantum Cascade Laser with Widely Tunable Wavelength

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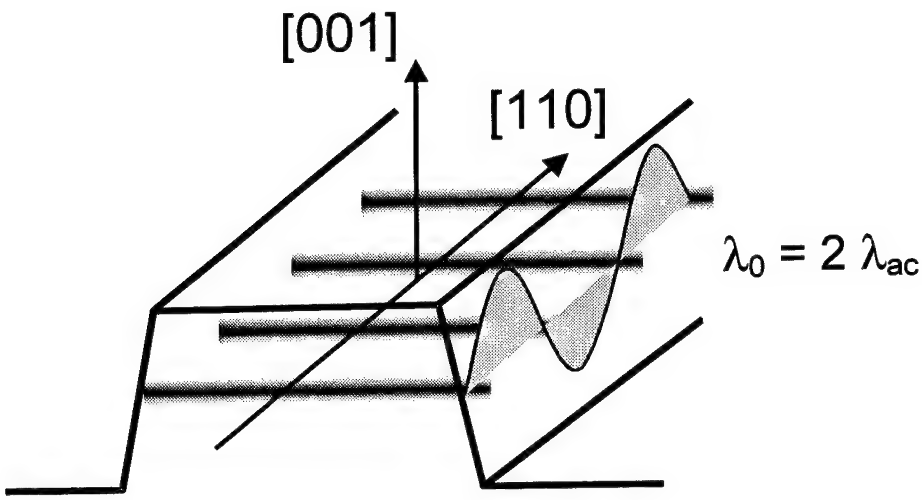
Quantum cascade lasers have the unique property that carriers in the active region form a unipolar plasma. This plasma can be manipulated by an external electric field. Coupled with the piezo-electric property of the laser materials, such as III-V heterostructures, this opens the possibility of engineering useful acoustoelectric interactions. This possibility was already envisaged in the fundamental Bell Labs patent[1] on the QCL.



As illustrated in the figure above, a shear acoustic wave whose wavevector is along the optical axis of the laser, produces a periodic modulation of the carrier density and the optical gain which provides a distributed feedback effect. In contrast to bipolar lasers, the piezoelectric modulation of unipolar carrier density is not accompanied by a degradation of the average gain. Exemplary calculations[2] for In(Al)GaAs QCL show that mode suppression ratio exceeding 30 dB is possible with reasonable acoustic power.

The main Bragg mode occurs at the wavelength λ_0 (in the medium) which is twice the period λ_{ac} of gain modulation imposed by the acoustic wave. Inasmuch as the acoustic frequency can be easily changed, the wavelength of the main DFB mode can be tuned in a wide range. This property should be very attractive for spectroscopic applications of the quantum cascade laser, especially in light of the recently demonstrated broadband QCL emission[3] in the wide range of 5-8μm.

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NOTES

Quantum Cascade Photonic-Crystal Microlasers

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We present a surface-emitting photonic-crystal Quantum Cascade (QC) laser. A photonic crystal lattice is incorporated within a QC heterostructure to create a laser emitting on a band-edge mode, which employs a two-dimensional distributed feedback effect.

Due to the transverse magnetic polarization of intersubband transitions, QC lasers cannot be designed as conventional surface-emitting lasers. However, in our case direct surface emission is obtained because the two-dimensional photonic crystal is used to form a micro-resonator that simultaneously provides feedback for laser action, and diffracts light vertically from the surface of the semiconductor surface.

The combination of size reduction, vertical emission, and lithographic tailorability of the emission properties enabled by the use of a high-index contrast photonic crystal resonant cavity can be interesting for applications in the mid- and far-infrared. In addition, the use of electrical pumping in these devices opens up another dimension of control for fundamental studies of photonic crystal and surface plasmon structures in linear, non-linear, and near-field optics.

NOTES

Material systems for quantum cascade lasers

Carlo Sirtori

The role of the material system on QC laser performance is still quite puzzling. At present, we have been able to demonstrate laser action in three different heterostructures: GaInAs/AlInAs//InP, GaAs/AlGaAs//GaAs and recently AlSb/InAs//InAs. Although it is unquestionable that the best results have been obtained using structures grown on InP substrates, the physical reasons that grant this supremacy are not apparent. It is obvious that a combination of physical parameters and device properties plays the main role, but there is no evidence about the weight of the different contributions.

However, at wavelengths < 4μm and in the THz region the search for the most appropriate material systems is still not definitive. Indeed, THz QC lasers are made only in GaAs based heterostructures.

We will present results on the three different material systems and compare their merits and drawbacks. In conclusion we will give some perspectives on new material systems for future quantum cascade lasers.

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Enhancement of the Phonon Depopulation in Intersubband Cascade Lasers

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The LO-phonon assisted depopulation of the lower lasing states in intersubband cascade lasers can be enhanced up to one order of magnitude by using the double electron-phonon resonance which has been proposed in our early work [1] and then successfully used by the MIT group for the implementation of their THz QCL [2]. To satisfy the double resonance condition, the depopulated subband of the active quantum well should be aligned with the second subband of the wider (reservoir) quantum well, while the energy separation from the first subband be tuned to the highest energy optical-phonon mode; see Fig. 1. The enhancement of the depopulation rate is achieved through the level anticrossing and resonant penetration of the electron states in adjacent wells.

A similar principle can be used for antimonide based QCL with type-II band alignment, as illustrated in Fig. 2. In such structures, the depopulated level should be located in the upper part of the heterostructure "leaky window" to prevent thermal backfilling of the lover lasing states. Such location makes the direct interband tunneling depopulation inefficient. We show that symmetry constraints for the interband phonon-assisted transition are essentially removed in type-II heterostructures by the band-mixing and subband nonparabolicity effects [3]. We show also that anticrossing of the electron and hole subbands in type-II structures allows for an optimum electron-phonon overlap which can be favorably combined with the peak value of the density of final states in the LO-phonon assisted interband transition thus making the rate of the transitions comparable with the rate of interwell phonon assisted transitions in traditional type-I intersubband heterostructures.

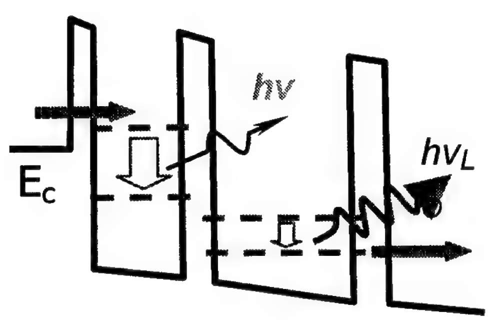

Fig. 1

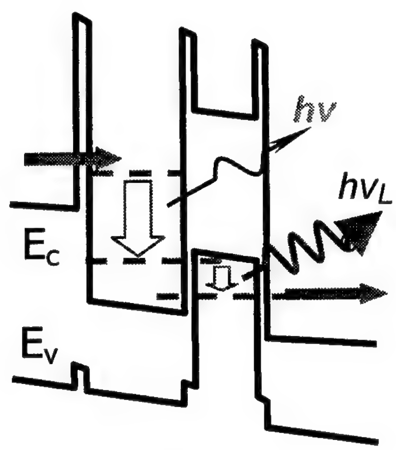

Fig. 2

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Towards Si-based Quantum Cascade Lasers: Challenges and Achievements

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Along with the successful development of intersubband transition based quantum cascade lasers (QCL) in the III-V material system, research activities have been started to adapt this concept to the Silicon (Si) material system to develop laser light sources which can be integrated with standard Si micro electronics. Key elements of such lasers are quantum wells from Si and Germanium (Ge), since their growth and processing is compatible with the fabrication of electronic devices as shown by developers of high-speed electronics.

Here, we will discuss the challenges of such a project where many technological and system inherent physical obstacles have to be mastered. To name the most important ones: - The 4% mismatch between the Silicon and Germanium lattice which produces large strain fields and thus involves growth of SiGe layers at extremely low temperatures on relaxed SiGe pseudo substrates with inherently high defect densities – The effective masses of the carriers in the SiGe system are relatively large, which implies low carrier mobility's and high ionisation energies (and related to this, strong free carrier absorption is expected) – finally, the band offset between strained Si and SiGe is stronger for the valence band, which led us to use p-doped structures in spite of the complexity of the band structure due to the coexistence of heavy, light and split-off (HH, LH, and SO) bands. In particular, this implies parasitic non-radiative relaxation channels for excited HH states via intermediate positioned LH bands.

We will present our recent achievements in the growth by MBE at low temperatures, T ~ 300 °C, of hundreds of strain compensated $Si/Si_{0.2}Ge_{0.8}$ multiple quantum wells lattice matched to a 50% SiGe pseudo substrate. Interface roughness at the Si/SiGe interfaces of 0.6 nm has consistently been determined by TEM, XRD and Hall mobility studies in narrow QW. We realized and characterized the transport and emission properties of complex injector structures of the bound to continuum type in Si/SiGe structures strain compensated to the pseudo substrate and studied the anti-crossing behaviour of the intersubband resonance in double QW coupled via a 11 Å thick barrier. Moreover, we investigated the free carrier absorption in bulk contact layers and compared this with multi QW 2D hole gases. The aim is to predict realistic waveguide losses for edge-coupled cavities with Ge-based top cladding layers. We started to investigate the importance of the interspersed HH and LH states for injection and lasing upper state lifetime by magneto tunneling spectroscopy.

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Intersubband Quantum-Box Semiconductor Lasers

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Intersubband Quantum-Box (IQB) semiconductor lasers are devices proposed[1] for solving the problem of inherently low wallplug efficiency of quantum-cascade (QC) lasers. The devices rely on the fact that 3-D quantum confinement can significantly suppress phonon-assisted transitions, which in turn increases the electron relaxation time by a factor of 20 or more. Then a *single-stage* IQB device provides as much gain as a 30-40 stage QC device, at much lower voltage. The main consequences are: 1) the electron injector and the Bragg mirror/transmitter can be independently optimized; 2) the wallplug efficiency, η_p, is much higher than for QC devices. Conservative calculations[1] show that IQB devices could operate CW at room temperature (RT) with low threshold-current densities (0.5-1.0 kA/cm^2) and with wallplug efficiencies in the 18-24% range. By comparison , the best reported η_p value at RT from QC devices is 0.4% and it happens only around $\lambda = 9\mu m$.

Preliminary Results

Room-temperature electroluminescence in the mid-IR ($\lambda = 4.7\mu m$) from single-stage intersubband GaAs-based edge emitters.

We report on the first realization of RT mid-IR (3-5 µm) emission from *single-stage* intersubband devices. The emission is comparable to that from 30-stage QC devices[2] and as narrow (i.e. 18 meV FWHM) as the best values reported from QC devices.[3,4] In addition the ratio of emissions at 80K and 300K is as low as 2.0.

The results are achieved by using deep active QWs (i.e. $In_{0.3}Ga_{0.7}As$) and tall barriers (i.e. $Al_{0.8}Ga_{0.2}As$), which virtually suppress any carrier leakage to the continuum. The active region consists of 2 QWs, and there is *no need* for a DBR mirror/transmitter region. For current densities of 1.6kA/cm^2 the voltages are as low as 0.8V. (80µm-wide contact stripes and 300µm-long cavity length)

Nanodot patterning.

2-D arrays of 35nm-diameter dots/posts on 100nm centers have been made by direct e-beam writing in photoresist and transferred into a dielectric mask via RIE.

In-situ etching and preferential regrowths.

Controlled *in-situ* gas etching of 30nm-deep trenches and regrowth of high-resistivity GaAs material, in an MOCVD system, have been demonstrated. This will now be used for QB formation in conjunction with the dielectric masks made via e-beam lithography and RIE.

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Self-Organized Epitaxial Nanostructures for Quantum Dot Cascade Lasers

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Quantum dots (QDs) may represent the next generation of quantum cascade lasers. The QD active material presents two significant advantages over planar heterostructures. First, a QD's three-dimensional quantum confinement open true energy gaps between the electron levels, and these energy gaps can exceed an optical phonon energy. Secondly, the intralevel dipole transition between the ground and first excited electron states in a self-organized QD is expected to lie in the plane of the crystal growth enabling surface emission. Both these new physical features of intralevel transitions in unipolar injection QD heterostructures make them very attractive for novel types of QD cascade lasers (QDCLs).

In this talk we will cover the design issues that may be important to realize QDCLs and QDC-VCSELs. Gain calculations will be presented that include realistic values of the QD density, estimates of the expected dipole transition strengths, and inhomogeneous broadening to show that self-organized QDs are well within the needed requirements to achieve QDCLs and even QDC-VCSELs. Laser designs will be presented and discussed as to their benefits.

Most important is the design of the QD gain stage and its contrast to the unipolar injection planar heterostructure. In the planar heterostructure a superlattice injector is used to form minibands to restrict and insure electron injection into those k-states normal to the crystal growth plane that possess a strong dipole transition for infrared light emission. However, in the QD heterostructure it is most important to obtain a rapid depletion from the ground electron state, while it is proposed that electron injection can be achieved through relaxation over a bulk barrier. We believe that the choice of the material system is key in order to achieve rapid relaxation from the QD's electron ground state, and will be difficult to achieve with GaAs-based heterostructures and self-organized InAs or InAlAs QDs. InP-based heterostructures appear much more attractive since the In(Al)As QDs can have ground electron states above the InP lattice-matched InGaAs. This makes InP-based InAlAs/InGaAs superlattices much more attractive for unipolar QDCLs if high quality In(Al)As QDs can be developed on this material system.

We will also present results of unipolar QD heterostructures and light emission characteristics from various groups, and review work on QD materials development in both GaAs-based and InP-based nanostructures. We show that it appears that the results from most groups do not yet utilize the important radiative transitions of the QDs to see the two important changes in the physics, namely the phonon bottleneck and the vertical emission based on unipolar QD heterostructures. In this context the necessary materials approach needed to observe these transitions will be described.

The work at UT Austin has been supported by the DARPA WASSP program.

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Ultimate limits in mid-infrared and Thz QC lasers

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Quantum cascade lasers are now turning ten, and has lived through and even passed beyond many of its early promises. Operation on a very wide frequency range, from 3.5 to 150µm, is a reality. Continous wave operation at room temperature and above has been realized, and recently extremely large optical power levels have been demonstrated. QC lasers operating on GaAs, InP, InAs-based materials have successfully been demonstrated, with work on Si and GaN in progress.

In this work, the fundamental limitations of QC lasers will be discussed, with new experiments done in extreme ratio of magnetic confinement to subband confinement, as well as experiments probing the effect of second-order gain on the performances of devices.

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Terahertz Quantum Cascade Lasers

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Terahertz radiation (1-10 THz) has proven to be a versatile tool in spectroscopy and sensing, in medical imaging and industrial process control, and in security screening. Yet, the exploitation and exploration of these fields has been hampered by the lack of appropriate, convenient sources. Already at its first demonstration, the quantum cascade laser (QCL) was recognized to be a promising candidate for the development of a THz emitter that can overcome the above-mentioned limitations. On the route towards a THz QCL, however, there were two main challenges to address: the achievement of gain (i.e. population inversion) at photon energies below the reststrahlenband and the design of a waveguide with low propagation losses and capable of confining the laser light to a epilayer thickness compatible with MBE growth.

These issues were recently addressed by the use of chirped superlattices (CSL) as an active medium and a partially metallic waveguide based on surface plasmons. These first devices emitted at 4.5 THz with peak powers of up to 2 mW and could be operated up to 50 K. Improvements in fabrication lead to cw operation with powers up to 4 mW and pulsed operation up to 75 K. A similar active region allowed for lasing at 3.5 THz. Lasers based on a bound-to-continuum (BTC) design were introduced by Scalari et al. for emission at 3.5 THz. Such structures were then used by various groups for lasers with emission frequencies down to 2.5 THz.

The design of CSL or of BTC transitions, however, does not appear to be a promising strategy for the achievement of higher operating temperatures. Most probably, high-temperature operation will need to rely again on the emission of optical phonons for a rapid depletion of the lower laser level. Williams et al. have demonstrated such a structure and achieved a maximum operating temperature of 140 K. However, these devices have high threshold current densities, most probably owing to insufficient control of the electrical transport. We present here a design based on interlaced photon- and phonon-emitting stages, which are connected by appropriate minibands that ensure good control of electrical transport. The lasers emit at 4 THz with peak powers up to 10 mW and can be operated up to 95 K, where the maximum operating temperature appears to be limited solely by the maximum current density. We find the slope efficiency to be virtually independent of temperature, indicating efficient extraction of electrons from the lower laser level at all operating temperatures. The threshold current density is almost comparable to that of a CSL or BTC design. We discuss possible improvements such as the implementation of a BTC transition to further reduce both the temperature dependence of laser operation and to suppress the detrimental premature alignment in the transport characteristics.

Finally, we give a brief report of distributed feedback THz QCLs with stable single-mode operation at 4.5 THz, for all injection currents and operating temperatures. Such devices are of great interest as local oscillators and in spectroscopy and sensing.

NOTES

Resonant-phonon-assisted THz quantum-cascade lasers using metal-metal waveguides for mode confinement

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The terahertz frequency range (1-10 THz) has long remained undeveloped, mainly due to the lack of compact, coherent radiation sources. Transitions between subbands in semiconductor quantum wells were suggested as a method to generate long wavelength radiation at customizable frequencies. However, because of difficulties in achieving population inversion between narrowly separated subbands and mode confinement at long wavelengths, THz lasers based on intersubband transitions were developed only very recently. The first THz quantum cascade lasers were developed based on a chirped superlattice structure. Recently, taking a completely different approach, we have developed THz quantum-cascade lasers based on resonant-phonon-assisted depopulation and using metal-metal waveguides for mode confinement. The schematics of both features are illustrated in Fig. 1. Based on the combination of these two unique features, we have developed many THz QCLs with record performance, including a maximum pulsed operating temperature at 137 K (Fig. 2), a maximum cw operating temperature at 93 K (Fig. 3), and the longest wavelength (~141 μm) QCL to date without the assistance of magnetic fields (Fig. 4). We will present more details and perspective at the workshop.

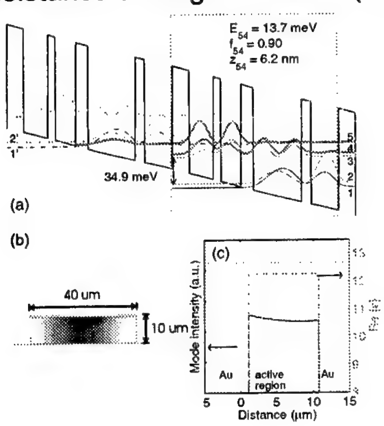

Figure 1. (a) Band diagram of a resonant-phonon THz QCL structure. (b) 2D mode profile of a metal-metal waveguide. (c) 1D mode profile of the

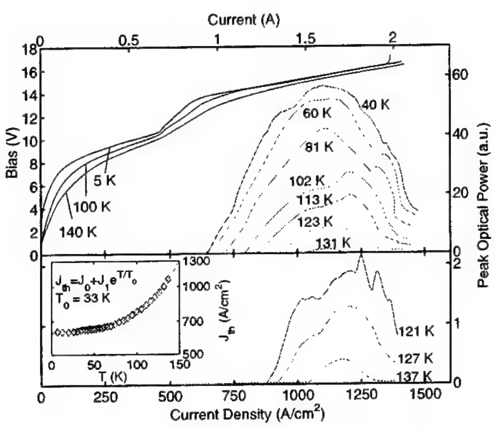

Figure 2. Pulsed power-current and voltage-current of a 3.8-THz laser device taken up to 137 K.

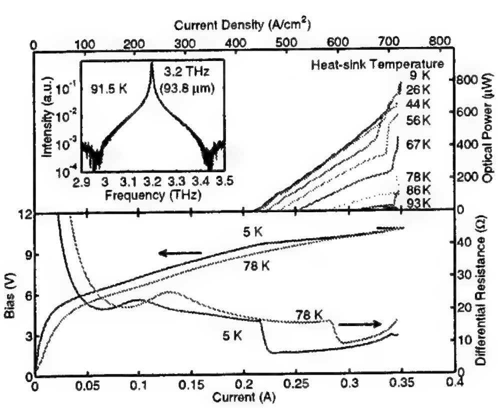

Figure 3. CW power-current and voltage-current of a 3.2-THz laser

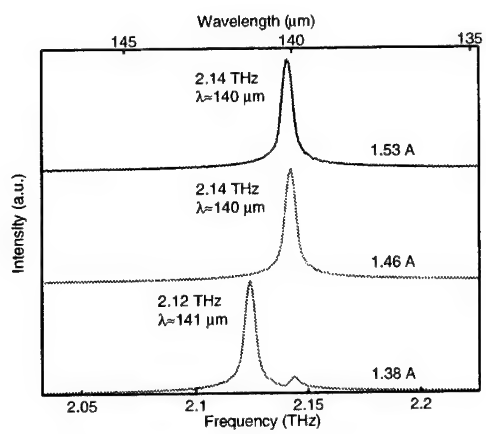

Figure 4. CW emission spectra of a laser device with λ ≈ 141 μm.

NOTES

Terahertz Quantum-Staircase and Quantum-Parallel Laser Designs for GaAs/AlGaAs and SiGe/Si

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Design results are presented for two new unipolar *pip* or *nin* intersubband lasers designed to emit in the 20 to 100 μm wavelength range (15 to 3 THz). The quantum staircase laser (QSL) is a highly simplified injectorless cascade having one to three QWs per period. The quantum-parallel laser (QPL) uses inter-miniband radiative emission from a flatband superlattice (SL) of identical QWs. A low bias voltage bucks out the built-in pp^+ or nn^+ potential, giving flat minibands. At these long wavelengths, QPLs and QSLs require several □m of MQW for good overlap of the gain profile with the fundamental THz mode. This thick epitaxy is a challenging requirement. In the GaAs QPL, the electron mean free path is about 100 nm; hence, ballistic transport of injected carriers will not be maintained if the SL length exceeds 100 nm. For efficient transport and mode overlap in a ~4000 nm stack, we propose a "super superlattice" QCL consisting in GaAs/AlGaAs of 100-nm undoped SLs joined by *n*-doped graded-composition AlGaAs miniband-resonant tunneling barriers that form an *ninin...in* diode. The energy difference across the grade allows CB1-electrons from one SL to tunnel into CB2 of the next SL. The QPL photon energy is less than the LO phonon energy. Two important *pip* QSLs were developed in collaboration with the University of Leeds team for SiGe/Si MQWs grown strain-balanced on an SiGe buffer: (1) a biased MQW of identical QWs wherein holes in HH2 of a given QW make a diagonal inter-well radiative transition to LH1 of the adjacent QW, providing a non-resonant cascade; (2) a staircase of three coupled QWs per period having three subbands engineered for level-3-to-level-2 THz lasing (HH2-LH1) and for rapid depopulation of the lower laser level-2 by means of 2-1 resonance (LH1-HH1) with the 64 meV Si-Si optical phonon modes. A similar depopulation technique has already been proven by the MIT team for GaAs conduction subbands. MIT used the 36 meV LO phonon resonance. In very recent "nitride work," Greg Sun and I have designed a unique 3-level *nin* QSL in $GaN/Al_{0.15}Ga_{0.85}N$ that has three coupled GaN QWs per period, internal electric fields, resonant tunneling at 70 kV/cm bias, 28-meV laser photons (3 to 2) and a 91 meV 2-to-1 separation. Fast depopulation of level-2 via emission of the 90 meV LO phonons offers the prospect of CW room-temperature operation for this novel QSL.

NOTES

THz Quantum Cascade Laser Design and Application

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Active THz imaging at 0.3 to 5 THz using synthetic aperture radar concepts may be useful to a variety of homeland security threats. As shown in Fig. 1, radiation in this band is able to penetrate clothing and produce a high signal-to-noise ratio image that can easily detect a concealed weapon from a distance of 25 meters. Other imaging applications include non-destructive chemical and object analysis through envelopes and cardboard boxes as well as the detection and identification of ground, airborne and exo-atmospheric mini-vehicle treats. In order to successfully implement THZ quantum-cascade lasers in the these systems the issues of stability, general beam quality/brightness, bandwidth and operating temperature/efficiency all must be addressed along with novel passive-optical transition and filter elements to couple the device to the rest of the system.

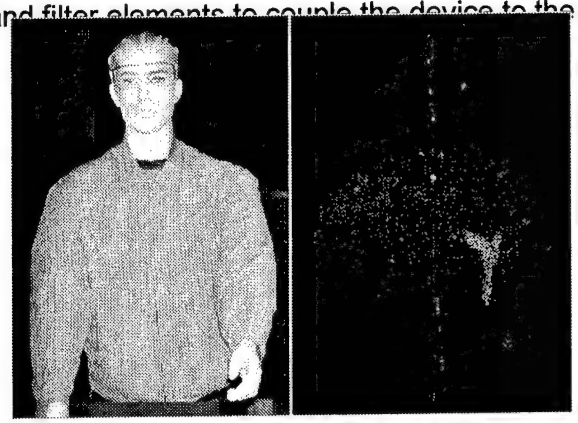

Figure 1. Mannequin with concealed weapon on the left and 1.56 Active THz image of same on the right.

The first part of the presentation will describe the active systems envisioned and compare the performance expected from AlGaAs/GaAs-based cascade devices vs. compact gas-cell sources. THz photonic crystals for waveguides, transition elements and surface emission will also be brought into the picture. The second part of the presentation will focus on the design of cascade devices to meet system needs and our initial attempts at fabricating such devices.

Modeling of electron-phonon interactions involving both confined phonon and interface phonons is in progress and we are in the process of building a complete model with the Schroedinger-Poisson solver. The last stage of the numerical modeling is the calculation of the gain in the quantum cascade structure and the solution of the rate equations. This work is ongoing. The need for optimization is very clear. We have to optimize the gain in the laser by designing the layered structure while minimizing the effects of *ee*-scattering and minimizing the required current injection for laser threshold. This is a substantial optimization problem (50~100 design parameters) and a genetic algorithm approach is being used to narrow our search. While working on the models we have developed two non-optimized 4-well cascade designs that we have begun to fabricate into devices. Our progress in fabricating these devices will also be presented along with problems that we have encountered in the project.

NOTES

Field Control of Quantum Cascade Lasers

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Quantum Cascade Lasers (QCL) have proven their suitability to cover the infrared and THz spectral range. However, quantum cascade lasers are also very interesting systems to study physical phenomena. We study the influence of external fields like magnetic fields or optical fields to control QCLs.

A strong magnetic field, applied perpendicularly to the superlattice planes, leads to an additional quantization of the in-plane electronic motion and creates a discrete ladder of Landau levels for each subband, which leads to a modification of the density of states and subsequently – of the scattering properties. The emission intensity of our THz QCL versus sample bias voltage and sample magnetic field shows an interesting behavior. With increasing magnetic field the intensity shows an increase of the emission power and the threshold is decreased [1]. This effect is attributed to the reduced dimensionality which changes the phase space for elastic scattering processes. Lasing is completely suppressed for certain magnetic fields for which the magneto-intersubband resonance condition is met. The study of the magneto-conductance shows also oscillations. We observe even a resonance for one half of the cyclotron resonance energy [2]. Based on these results we will discuss the importance of electron-electron scattering for the performance of THz QCLs.

The laser emission spectra recorded with an FTIR spectrometer at different magnetic fields show a blue- and a red-shift. The observed red-shift at high magnetic fields is not bias-related, because it is observed both in constant current and constant voltage conditions. The origin of these shifts can be due to many-body effects (depolarization shift) or due to a subtle interplay between inversion gain and Bloch gain.

In addition, we have studied the influence of optical pulses on the intersubband transition. We have measured the transient intersubband absorption of a coupled quantum well after pulse excitation. We couple two subbands through a coherent superposition which is generated by band gap excitation with short 12 fs laser pulses. The transition to an empty third subband is probed by THz time-domain spectroscopy. Due to two equivalent paths for the absorption quantum interference effects are predicted. For short delay times we observe indeed reduced absorption which is a typical sign for quantum inference. These results are very interesting for the modulation of QCLs by external ultrafast lasers.

[1] V. Tamosiunas, R. Zobl, J. Ulrich, K. Unterrainer, R. Colombelli, C. Gmachl, F. Capasso, K. West, L. Pfeiffer, Appl. Phys. Lett., 83, 3873 (2003).

[2] K. Kempa, Y. Zhou, J.R. Engelbrecht, P. Bakshi, H.I. Ha, J. Moser, M.J. Naughton, J. Ulrich, G. Strasser, E. Gornik, K. Unterrainer, Phys. Rev. Lett. 88, 226803(2002).

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A Physical Model of Quantum Cascade Lasers: Application to GaAs, GaN and SiGe devices

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The philosophy behind this work has been to build a predictive `bottom up' physical model of quantum cascade lasers (QCLs) for use as a design tool, to interpret experimental results and hence improve understanding of the physical processes occurring inside working devices and as a simulator for developing new material systems. The standard model uses the envelope function and effective mass approximations to solve two complete periods of the QCL under an applied bias. Other models, such as k.p and empirical pseudo potential, have been employed in p-type systems where the more complex band structure requires it. The resulting wave functions are then used to evaluate all relevant carrier--phonon, carrier--carrier and alloy scattering rates from each quantised state to all others within the same and the neighbouring period. This information is then used to construct a rate equation for the equilibrium carrier density in each sub band and this set of coupled rate equations are solved self-consistently to obtain the carrier density in each eigenstate[1]. The latter is a fundamental description of the device and can be used to calculate the current density and gain as a function of the applied bias and temperature, which in turn yields the threshold current and expected temperature dependence of the device characteristics[2]. A recent extension which includes a further iteration of an energy balance equation also yields the average electron (or hole) temperature over the sub bands [3].

This presentation will review the method and describe its application to mid-infrared and Terahertz, GaAs, GaN, SiGe and automated optimised quantum cascade laser designs.

[1] D. Indjin, P. Harrison, R. W. Kelsall and Z. Ikonic, `Self-consistent scattering theory of transport and output characteristics of quantum cascade lasers', J. Appl. Phys. 91, p9019 (2002)
[2] D. Indjin, P. Harrison, R. W. Kelsall and Z. Ikonic, `Self-consistent scattering model of carrier dynamics in GaAs-AlGaAs Terahertz quantum cascade lasers', IEEE Photonics Tech. Lett. 15, p15 (2003)
[3] P. Harrison, D. Indjin and R. W. Kelsall, `The electron temperature and mechanisms of hot carrier generation in quantum cascade lasers', J. Appl. Phys. 92, p6921 (2002)

NOTES

Ultrafast coherent electron transport in quantum cascade structures

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The wave nature of electrons in solids gives rise to transport processes which are governed by the coherence properties of the electron wave function. Quantum transport phenomena like resonant tunneling occur typically at very low carrier concentrations where decoherence processes are comparably slow. Most optoelectronic devices work, however, at elevated carrier densities (> 10^9 cm^{-2}) where electron-electron and electron-phonon scattering are expected to result in a rapid loss of quantum coherence.

The quantum cascade laser (QCL) is an important prototype system showing coherent quantum transport even at elevated densities. Although the design and production of these structures have reached a high degree of sophistication, direct experimental information on the underlying microscopic mechanisms is still poor. A key issue for the device performance - which has to be reconsidered for every new material system - is the transport of electrons from the injector into the upper laser level. Optimum design strategies try to enhance the injector–active-region coupling via resonant tunneling and to prevent the carriers from propagating into the continuum. The underlying physical picture relies on coherent electron transport, which has been experimentally demonstrated very recently [1]. The degree of coherence in quantum transport (coherent resonant tunneling vs. incoherent transport via scattering) is determined by the interplay between electron wavepacket propagation and dissipative scattering processes. Different theoretical pictures have been developed for electron transport from the injector into the active region, invoking either coherent resonant tunneling or incoherent transport through the injection barrier.

Recently, we developed a novel experimental concept which allows us to study directly time-resolved the transport from the injector into the active region [1]. The nonlinear depletion and recovery of optical gain is studied in mid-infrared pump-probe experiments on three different GaAs/AlGaAs QCL structures under current injection. Strong gain oscillations originating from coherent electron motion between the injector and the active region give evidence for the coherent character of charge transport under typical working conditions of a QCL. The oscillation frequency is determined by the height and width of the injection barrier. The amplitude and the decay rate of the observed gain oscillation are a direct measure for degree of coherence of the underlying quantum transport.

More recent studies show that the degree of coherence is quite sensitive to various external parameters. For low current densities, low lattice temperatures and low pump pulse intensities, the charge transport is dominantly coherent, leading to pronounced gain oscillations due to the coherent motion of electron wave packets. For higher current densities, lattice temperatures, or pump intensities, the gain recovery shows an additional incoherent component, which essentially follows the pump-induced heating and subsequent cooling of the carrier gas in the injector. The strong damping of the oscillation is mainly due to carrier-carrier scattering in the injector. At elevated lattice temperatures carrier-carrier scattering becomes more efficient and, additionally, carrier-phonon scattering occurs. As a result, both the oscillation amplitude and the lasing efficiency of the device decrease.

In conclusion, our data clearly show that even at the high electron densities present in a quantum cascade laser the coherence properties of the electron wave function play a very important role for transport. Our experimental technique is a new tool to investigate the transport in QCLs - a key issue for exploring new material systems and wavelength ranges.

[1] F. Eickemeyer et al., Phys. Rev. Lett. **89**, 047402 (2002)

NOTES

Electronic Transport in Quantum-Cascade Heterostructures

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Quantum-cascade lasers rely on the injection of electrons, via tunneling, into an excited state of an *active* quantum-well (or superlattice) region, followed by the electrons' radiative decay to a lower quantum state in that region. Although the emission process has been studied extensively and by now is almost optimized, the details of the electron transport have received much less attention. This process is complex, however, involving tunneling through single potential barriers, resonant tunneling in coupled quantum wells and even superlattice transport.

In this talk I'll highlight recent experimental results pertinent to those transport mechanisms. In particular, I will show evidence of a new tunneling mechanism in coupled quantum wells that leads to negative differential conductance (NDC) and is the stronger the higher the temperature, so that while absent at T<150K it can dominate the current-voltage characteristics at 300K and above. I will also use new tunneling and photo-tunneling data to illustrate how the measurement of *shot noise* is helping us to understand better tunneling in multiple-barrier structures and even superlattice transport. Finally, using temperature-dependence results, I will discuss the effectiveness of a superlattice to prevent electrons from tunneling out of the active region of a quantum-cascade structure before they decay radiatively.

NOTES

Mode Locking of Quantum Cascade Lasers

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The principles of mode locking are discussed in the context of mode locking of the Quantum Cascade Laser. The key parameters of the gain medium in Quantum Cascade Lasers such as fluorescence liftime and gain cross section are very much different from solid-state as well as interband semiconductor laser materials which makes single pulse mode locking of these novel class of lasers difficult. On the other side intraband transitions open up the possibility to engineer ultrawideband gain media to approach even single-cycle pulse generation directly from a compact source in the 3-20 micron wavelength range. For such short pulses coherent interaction with the intraband transistions can no longer be neglected. The challenges in describing and understanding the recently reported results on picosecond pulse generation in QCLs will be discussed.

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Modelocking of broadband QC lasers*

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Active mode-locking in broadband Quantum Cascade (QC) lasers with a repetition rate of about 14.3 GHz has been achieved through the modulation of the laser bias current. At low driving currents the active mode-locking in broadband (QC) lasers resembles the active mode-locking in single wavelength QC lasers, while at high driving currents the mode-locking properties are governed by the broad spectral gain of these lasers. At high bias currents the active modulation excites and phase-locks Fabry-Perot modes across the entire gain spectrum in the spectral range between 6.7 and 7.4 μm. The broad spectral width of the actively mode-locked lasers ($\Delta\nu > 2$ THz) demonstrates the potential for generating subpicosecond pulses, and the variation of the spectra with modulation frequency allows a direct measurement of the group refractive index dispersion as $+9\times10^{-3}\ \mu m^{-1}$. Data from passively modelocked broadband QC lasers will also be discussed.

* Collaborators: Alex Soibel, Claire Gmachl, Milton L. Peabody, A. Michael Sergent, Roberto Paiella, Harold Y. Hwang, Deborah L. Sivco, Alfred Y. Cho, H. C. Liu, Christian Jirauschek and Franz X. Kärtner.

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